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Project-based storage capacity and project maturity

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Abstract

The preparation of reasonable estimates of CO_2 storage capacity is a key task for engineers and geoscientists seeking the large-scale deployment of CCS as a greenhouse gas reduction measure. This study considers how project maturity and injection rate affect capacity estimates and the likelihood of economic viability. We do this by examining the effect of appraisal using decision tree analysis and examine the effect of injection-rate on the probability of successful project development and economics. Our proposed methodology is used to examine a hypothetical CO_2 transport and storage site. This form of project analysis provides information to project developers on the likelihood of a project being economically viable, as well as guidance on determining the scale of projects to develop.

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Keywords: Storage capacity classification; Techno-economic assessment; Carbon capture and storage (CCS)

1. Introduction

Carbon Capture and Storage (CCS) is considered as one of the key CO_2 abatement technologies [1]. Whether there is sufficient CO_2 storage capacity to allow CCS to play a significant role in mitigating climate change has been a subject of discussion since 1990s [2]. Numerous independent investigations indicate that sufficient pore space exists to store many thousands of gigatonne (Gt) of CO_2 [2, 3]. However, the extent to which that pore space can be practically utilised at a technically and economically feasible injection rates continues to be a subject of debate in the literature.

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Further, there has been an ongoing discussion on the appropriate methodology for estimating geological CO_2 storage capacity. The basis of most CO_2 storage capacity methodologies is to determine the pore space available for storage. Some adopt a probabilistic approach based on Monte Carlo Simulations [4, 5]. Some studies conduct injectivity analyses to determine the portion of the pore volume that is "technically accessible" for CO_2 storage [6]. However, economics and the uncertainties associated with economic factors are ignored in most literature.

In an earlier paper [7] we argue that the most appropriate means of producing rigorous estimates of CO_2 storage capacity is by combination of geological, reservoir engineering and economic analyses. In this paper we extend our treatment of storage capacity [7, 8] by considering the effect of project maturity. The approach we take is aimed at individual storage projects or networks rather than basin scale or formation-wide estimates of capacity. We examine two stages in the project development process – pre-appraisal and post-appraisal – to examine how capacity estimates may change as more information is gained and as designs are refined.

2. Capacity classification

We developed an approach to estimating CO_2 storage capacity which closely follows the internationally accepted approach for oil and gas reserves estimation, namely the Petroleum Resource Management System (PRMS) recommended by the Society of Petroleum Engineers [9]. Our approach leads to a capacity classification system, known as the Carbon Storage Capacity Management System (CSCMS) shown in Figure 1. This classification system and its associated methodology not only consider geological properties but also incorporate engineering and economic factors throughout the capacity estimation and classification process.

<table>
<tr><td rowspan="6">Verified Storage Volume</td><td rowspan="3">Commercial</td><td colspan="3">Injection</td></tr>
<tr><td colspan="3">Commercial Storage Capacity</td></tr>
<tr><td>Proved
(1P)</td><td>Proved plus probable (2P)</td><td>Proved plus probable plus possible (3P)</td></tr>
<tr><td rowspan="3">Sub-Commercial</td><td colspan="3">Contingent Storage Capacity</td></tr>
<tr><td>Low estimate
(1C)</td><td>Middle estimate
(2C)</td><td>High estimate
(3C)</td></tr>
<tr><td colspan="3">Inaccessible</td></tr>
<tr><td colspan="2" rowspan="3">Unverified Storage Volume</td><td colspan="3">Prospective Storage Capacity</td></tr>
<tr><td>Low
estimate</td><td>Middle
estimate</td><td>High
estimate</td></tr>
<tr><td colspan="3">Inaccessible</td></tr>
</table>

← Range of uncertainty →

Fig. 1. The classification of storage capacity under CO_2 Storage Capacity Management System

An important point to note about the CSCMS is that it is fundamentally project-based in a similar way to the PRMS when classifying oil & gas resources. For instance, under the PRMS in order to be able to report "Reserves", or "Contingent Resources" or "Prospective Resources" there must be a market or a potential market for the oil or gas produced. This condition is required even though the amount of oil or gas that can be marketed is uncertain. In the same way, in the case of CO_2 injection, there must be a source or sources of CO_2 that need to be stored in the site even though the rates of emissions from those sources are uncertain. Prospective estimates may be based on pre-commercial and exploration data that doesn't necessarily target the formation in question.

The CSCMS at its most basic level classifies capacity into Unverified and Verified Storage Volumes. The unverified storage amounts consist of the estimates of prospective storage capacity. Prospective Capacity is the capacity which is could be available to future projects where the existence or suitability of geological formations for storage has not been verified.

In the Verified Storage Volume domain, the capacity is sub-divided into Contingent and Commercial Storage Capacity. Verified storage volumes are those available in known sub-surface formations. This verification is largely achieved through appraisal activities which include, but are not limited to, the drilling of exploration wells.

Contingent Capacity is the CO_2 that could be stored except that applicable carbon transport and storage projects are not yet considered mature enough for commercial development. In other words, the commercial development of the storage site is contingent on various factors being met. Such factors may include (1) the lack of an economic or regulatory incentive for CCS (e.g. a carbon price or emission intensity limits), (2) requirement for technology that is still under development or (3) insufficient information on the storage site to clearly establish a business case for injection.

Finally, there is Commercial Capacity. Commercial Capacity is the volume that is expected to be available for storage from a given date. Such capacity must also be (1) verified, (2) contain injectable rock volume with a low chance of leakage, (3) be remaining (as of the evaluation date) based on the project(s) applied and (4) be commercial. Essentially, for capacity to be classed as commercial, the proponents must be able to demonstrate a non-contingent positive net present value (NPV) for the storage project.

This paper we are primarily concerned with the movement from prospective to contingent capacity estimates through the process of appraisal.

3. Methodology

To examine the effect of appraisal on capacity estimates, we analyse the capacity of hypothetical CO_2 transport and storage project. This project is based on the results of source-sink matching studies centred on south-east Queensland conducted as part of the Australian Government's Carbon Storage Taskforce [10, 11]. For our analysis we assume that pure CO_2 is transported 380 km from a capture hub to a hypothetical storage site in the Surat Basin. Our key assumptions for the pre-appraisal stage are given in Table 1.

To estimate capacity we incorporate uncertain reservoir properties, injection rates, costs and carbon prices using Monte Carlo simulation involving 15,000 trials. Numbers of wells are determined using *MonteCarbon* [12] and economic calculations are performed using the *Integrated Carbon Capture and Storage Economics Model (ICCSEM)* both of these tools were developed at UNSW Australia for the CO2CRC. Further details of the calculations carried out in ICCSEM are provided elsewhere [13].

Key outputs of this process are probability distributions of the required numbers of wells and the Net Present Value (NPV). This is in contrast to more widespread techniques which produce a central estimate or a probability distribution of storage capacity. The reason for this is that for a storage project the key question is whether the storage site is capable of storing the probable project flows rather than estimating the maximum amount of CO_2 that may be effectively stored. The results of each Monte Carlo simulation trial can be assigned to one of three categories:

1. Technically infeasible – in these cases the combination of CO_2 flow-rates and geological properties result in unreasonably large numbers of wells,
2. Economically unviable – these are cases where the numbers of wells are reasonable but the combination of well numbers, project costs and carbon prices mean that the project NPV is negative, and
3. Economically viable – these are the remaining cases where a zero or positive NPV is returned.

On the basis of this estimate we could decide whether or not the project warrants further appraisal. This is important because appraisal is required to move to the next stage of capacity estimation. If we do not undertake appraisal, the project is not developed and the capacity of the storage site is zero.

However, if appraisal is undertaken then the formation may found to be more, less or similarly favourable for storage. These findings come in the form of changes in the estimated probability distributions for formation properties, although we expect a reduction in uncertainty (quantified in terms of smaller standard deviations).

Table 1. Pre-appraisal project properties assumed for our hypothetical transport and storage project.

Parameter	Units	Distribution	P90	P10
Areal extent	km^2	Log normal	30,000	38,000
Depth of base seal	m	Log normal	1,170	2,070
Formation thickness	m	Log normal	30	130
Permeability	mD	Log normal	100	2,500
Injection rate	Mt/y	Normal	10	25
Carbon price	A$/t	Log normal	7	57
Transport distance	km	Fixed	376	
Porosity	%	Fixed	20%	
Formation temperature	°C	Fixed	15°C + 30°C per km	
Formation pressure gradients	MPa/km	Fixed	10	
Fracture pressure gradient	MPa/km	Fixed	15	
Injection period	Years	Fixed	25	
Real discount rate	% pa	Fixed	7%	

Appraisal also affects the mean values of formation properties: the mean may go up, it could stay approximately the same or could go down. We analyse all the combinations of appraisal outcomes for each formation property using a decision tree. In this work there are four uncertain reservoir properties and three appraisal outcomes for the mean of each property. A decision tree considering all possible combinations would have 81 branches following appraisal.

In order to simplify the decision tree we ran a sensitivity analysis on the four uncertain properties in Table 1 and found that the two most important properties are permeability and formation thickness. Therefore, we limited our decision tree analysis to the effect of appraisal on permeability and formation thickness – a decision tree with nine branches following appraisal. Table 2 gives the pre-appraisal and the three post-appraisal values for permeability and thickness. Our treatment of appraisal is that it results in a standard deviation half the value of the pre-appraisal value and a mean equivalent to either the P90 (low outcome), the mean (mid outcome) or the P10 (high outcome).

Table 2. Post-appraisal project properties assumed for our hypothetical transport and storage project.

		Permeability (mD)		Formation thickness (m)	
		Mean	Standard Dev.	Mean	Standard Dev.
Pre-appraisal		1,100	2,156	74	46
Post-appraisal	Low	100	1,078	30	23
	Mid	1,100	1,078	74	23
	High	2,500	1,078	130	23

Having developed the results of appraisal, we then ran Monte Carlo simulations for each of the nine possible outcomes. Since the outcome of appraisal is unknown in our hypothetical example we must assign a probability to each of the appraisal outcomes. We consider two possible probability distributions. The first distribution of post-appraisal results we consider is uniform distribution of all combinations of permeability and formation thickness (approximately 11% for each combination of permeability and formation thickness). The second distribution we consider is skewed –the low values have a 50% chance of occurring, the mid values occur in 30% of cases and the high values in the remaining 10% of cases. These probabilities are then multiplied to give the probability of a particular outcome. For instance, for the combination of low permeability and low formation thickness the probability of that outcome is 25%.

4. Results and Discussion

4.1. Pre-appraisal

The results of applying our methodology to pre-appraisal data are given in Table 3. We found that there was a 70% chance of the project being commercially viable, while 17% of all cases were not technically viable and the remaining 13% of cases were technically feasible but not economically viable.

We also found that the average NPV of the project was A$3.3 billion with a standard deviation of A$5.0 billion. This value reflects a significant return on investment to the operator of transport and storage project who receives revenue for sequestering CO_2. The NPV is large but reflects the scale of the CO_2 injected over 25 years. The positive NPV and the large standard deviation demonstrate that it is worthwhile continuing to pursue the project but also the need for appraisal.

Table 3. Outcomes of decision tree analysis.

	Properties		NPV (A$ billion)		Probability of project outcomes		
	Permeability	Formation Thickness	Mean	Standard deviation	Technically unfeasible	Economically unviable	Economically viable
Pre-appraisal			3.3	5.0	17%	13%	70%
Appraisal outcomes	low	low	-6.8	15.4	69%	23%	9%
	mid	low	3.0	5.3	39%	12%	49%
	high	low	3.3	5.1	25%	10%	64%
	low	mid	0.84	7.4	20%	33%	47%
	mid	mid	3.4	5.1	3.4%	12%	84%
	high	mid	3.6	5.0	0.6%	11%	89%
	low	high	2.8	5.0	2.3%	24%	74%
	mid	high	3.5	4.9	<0.1%	11%	89%
	high	high	3.5	4.9	<0.01%	11%	89%
Post-appraisal with uniform probability			1.9	N/A	18%	16%	66%
Post-appraisal with skewed probability			0.35	N/A	29%	19%	52%

4.2. Post-appraisal

The results of our post-appraisal analysis are also given in Table 3. The results of appraisal demonstrate that when appraisal leads to Darcy-level permeabilities, the average and standard deviation of NPV is relatively insensitive to changes in formation thickness.

We also find that technical feasibility increases with permeability and formation thickness however, the effect is not linear. As shown in Figure 2, there is a significant improvement in technical feasibility when permeability increases from the low case to the mid case. The change in feasibility is smaller as permeability increases to the high case. Figure 2 also shows that feasibility is less sensitive to permeability as formation thickness increases. We also observe a similar pattern for economic viability. However, whereas the largest thicknesses almost ensure technical feasibility, they only lead to 90% economic viability at the most. This reflects the inevitability of cases with high costs and low carbon prices.

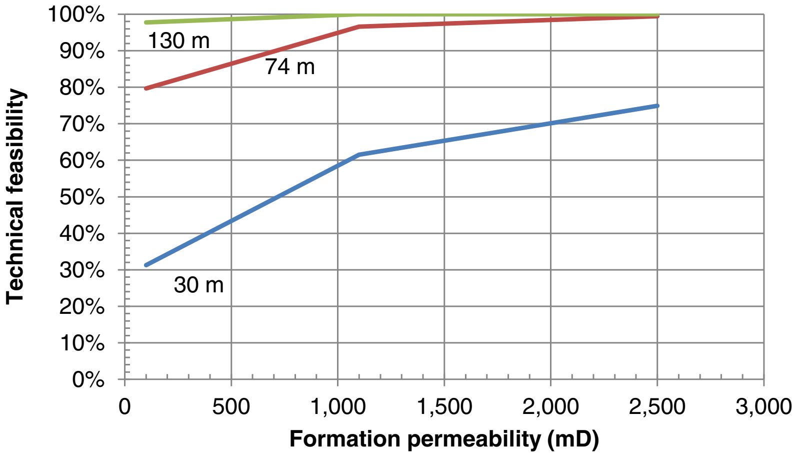

Fig. 2. The effect of changes in average permeability on technical feasibility for different average formation thicknesses.

Finally when we aggregate the appraisal outcomes, we find that the risk of a project being technical infeasible is approximately the same for both probabilities we assume for appraisal outcomes. However, there are significant differences in the likelihood of the project being economically viable. When a uniform probability is employed there is a 66% chance of economic viability but when a skewed distribution is used the probability decreases to 52%.

Appraisal also leads to a striking change in the NPV. Before appraisal, the expected NPV was A$3.3 billion. Following appraisal, the average NPV drops to A$1.9 billion with uniform distribution of outcomes, while with skewed outcomes the NPV drops to A$0.35 billion.

Both the results for outcome probabilities and for NPV reflect the greater weighting given to poor formation properties under skewed outcomes and thus to technically unfeasible and economically unviable outcomes, as well as NPV.

We find that the risk of the project being uneconomic is more strongly affected by permeability than thickness. This is because permeability has a strong impact on numbers of wells and therefore on project economics. Namely, as permeability decreases numbers of wells increases making the project more expensive and therefore requiring higher carbon prices to make the project viable. On the other hand, formation thickness has a greater impact on the risk of a project being technically unfeasible. With small thicknesses the actual space available for storage is limited and so pressure build-up in the formation is much more significant making it harder for the project to be technically feasible.

4.3. Injection rate and commercial viability

Up to this point we have assumed that the flow-rate is uncertain (as may be the case before a project is defined). However, in the conceptual design of many projects the likely injection rate is known with greater precision. Under our methodology, when the injection rate is fixed the capacity becomes the product of the injection rate and the numbers of years of injection. The methodology then only estimates the probabilities of the different project outcomes. To show this, we ran a second study where the injection rate is approximately uniformly distributed. The results in Figure 3 show the likelihood of each outcome as a function of flow-rate.

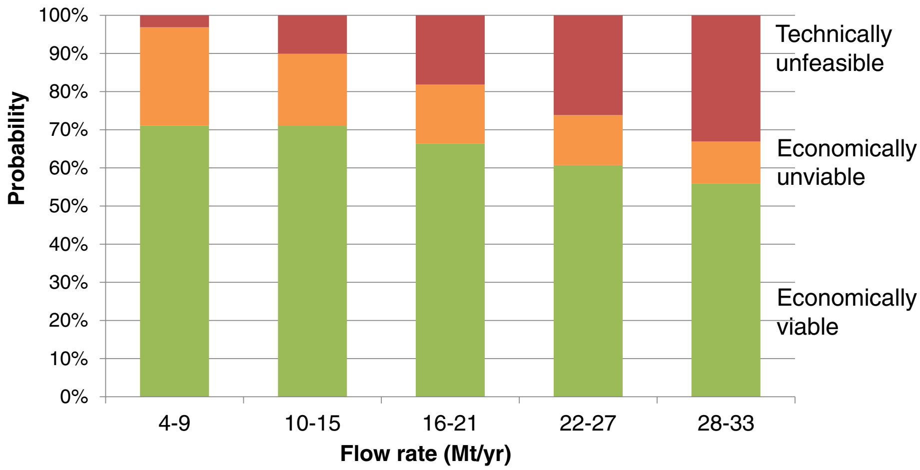

Fig. 3. Likelihood of project outcomes post-appraisal for different injection rates.

The results show that as flow-rate increases the risk of a project being technically unfeasible increases. At the same time, the likelihood of the project being economically viable decreases; the risk that the project may be economically unviable also decreases. This illustrates that, in the project being considered here, the diseconomies of scale in injection are overcoming the economics of scale in transport. However, the decrease in economic viability does not result in an increase in economically unviable cases but in more technically unfeasible cases. This is caused by the interaction between larger flow-rates making it harder for cases with poor or marginal formation properties to be technically feasible. The risk of the project being economically unviable is greatest when the injection rates are low. This is because there is limited revenue available to meet the significant costs of transport and storage. At low flow-rates it is easier for storage to be feasible because fewer wells are required.

Results such as those shown in Figure 3 are an important tool in the hands of project developers. These results enable decision makers to get a sense of the risk involved in developing projects of different scales. It may be that a project proponent chooses to reduce the scale of a project (and thereby the storage capacity) in order to ensure an acceptable change of economic viability. Alternatively, knowing that there are higher risks of losing money at large injection rates a project developer may choose to conduct further appraisal work, seek to improve the injectivity of the storage formation through pressure management or improve the project economics through seeking to reduce the project costs.

5. Conclusions

In this paper the effect of appraisal on classifying storage capacity estimates is examined. Storage site appraisal is pursued when exploration and analysis indicates there is there is the prospect of commercial storage capacity. Appraisal indicates whether or not a project is technically feasible and moves a storage site's capacity classification from being Prospective to being Contingent. Appraisal can increase or decrease the likelihood of commerciality. A methodology such as the one demonstrated in this paper provides important information around the likelihood of different project outcomes. Further, it illustrates the need to assess the chance of commerciality (economic viability) when reporting the storage capacity for CCS projects.

In our analysis of a hypothetical storage project in South-East Queensland, Australia we demonstrate that as a formation becomes more favourable, the risk of the site being technically or economically unsuitable goes down. The effect of changes in permeability and thickness is generally strongest when moving from low- to mid-level values. The risk of being not economically viable is more affected by permeability than thickness because of permeability's effect on the number of wells – this also affects the standard deviation. However, thickness has a stronger effect on the risk of technical unfeasibility, as it constrains the actual space available for storage.

We also find that as the injection rate increases, the likelihood of the project being not economically viable increases. One might decide to lower the injection rate to increase the chance of commercial success, which in turn reduces the storage capacity for the project.

Future work will demonstrate the sensitivity of project outcomes and capacity estiamtes to different assumptions around economics and injection rate. Moreover, technological improvements, cost reductions and/or increases in carbon price will increase the chance of development.

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